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APPLICATION

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TITLE: SLOTTED QUANTUM WELL SENSOR

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SLOTTED QUANTUM WELL SENSOR

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application serial no. 09/443,177, filed November 19, 1999, which claims priority from U.S. provisional application serial no. 60/109,329, filed on November 20, 1998.

ORIGIN

The devices and techniques described herein were made in the performance of work under a NASA contract, and are subject to the provisions of Public Law 96-517 (35 U.S.C. §202) in which the Contractor has elected to retain title.

BACKGROUND

This specification relates to quantum-well radiation sensors and techniques of constructing quantum-well radiation sensors with reduced noise.

An infrared quantum-well semiconductor sensor includes a quantum-well structure formed of alternating active and barrier semiconductor layers. Such a quantum-well structure can have different energy bands which each can have multiple quantum states. An intraband transition between a ground state and an excited state in the same band (i.e., a conduction band or a valance band) can be used to detect

infrared ("IR") radiation by absorbing IR radiation at or near a selected resonance IR wavelength. Only incident radiation with a polarization that is perpendicular to the quantum well layers can be absorbed, because this polarization can induce an intraband transition. The absorption of the radiation generates electric charge indicative of the amount of received radiation. The radiation-induced charge can then be converted into an electrical signal (e.g., a voltage or current) to be processed by signal processing circuitry.

The total charge produced by an IR quantum-well sensor generally includes two major contributions. One is radiation-induced charge which indicates the amount of radiation being absorbed by the quantum-well layers. Another contribution is the charge that is not produced by absorption of radiation. Rather, such non-radiation-induced charge is caused by thermal effects, quantum tunneling effect, shot noise, and other fluctuation processes. The motion of certain non-radiation-induced charge under a bias electrical field generates an electrical current called the dark current. This dark current is undesirable since it does not reflect the amount of radiation to be detected. In addition, it can saturate the detection circuitry and hence adversely affect the detection of the radiation-induced signal.

SUMMARY

The present devices and techniques use an array of quantum-well columns of either one dimension or two dimensions formed on a substrate to couple incident radiation to have a polarization perpendicular to the quantum-well layers for intraband absorption and to reduce the dark current.

In one embodiment, a quantum-well semiconductor device includes a plurality of quantum-well columns spatially separated from one another by a gap which is electrically insulating and formed over a substrate to form a periodic array. Each quantum-well column includes, a first conductive contact layer formed over the substrate, a quantum-well stack having a plurality of alternating quantum-well layers parallel formed over the first conductive contact layer and operating to absorb radiation polarized perpendicularly to the quantum-well layers, and a second conductive contact layer formed over the quantum-well stack.

These and other features and associated advantages of the devices and techniques are described in detail in the following.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows on embodiment of a 2-dimensional slotted quantum-well sensor having quantum-well columns separated by low-index insulating gaps.

FIG. 2 shows calculated absorption spectra of a slotted quantum-well sensor and a conventional grating-coupled quantum-well sensor without slots. The calculation is based on a coupled wave analysis by using the same level of anisotropic absorption: $n_x=3.1$, $n_z=3.1-j(\alpha_z\lambda/4\pi)$, $\alpha_z = 84cm^{-1}$.

FIG. 3 shows a structure of a 1-dimensional array of quantum-well columns having grating teeth.

FIG. 4 shows the calculated magnitude of the coupled radiation with its electric field (E_z) perpendicular to the quantum-well layers for a grating-coupled quantum-well sensor similarly constructed as in FIG. 2 but without slots.

sub C2 FIGS. 5 and 6 respectively show the calculated electric field (E_z) in the quantum-well layers for sensors with and without the grating teeth.

DETAILED DESCRIPTION

An intraband quantum-well sensor can be formed of an array of columnar shaped quantum-wells on a substrate. The columns can be arranged in a one dimensional array or in a two dimensional array. The columnar elements can be square, rectangular, round, elliptical or irregular in cross section each can be similarly shaped or they can be different. FIG. 1 shows one embodiment of such a "slotted" sensor 100 having a two-dimensional array of quantum-well columns 110 on a substrate 102. Any two adjacent quantum-well columns 110 are completely separated by a gap 120. Each quantum-well column 110 includes a first conductive contact layer 112 which is directly formed over the substrate 102, a quantum-well stack 114 of multiple alternating semiconductor layers (active and barrier layers) to absorb radiation at one or more wavelengths. The quantum-well layers are parallel to the surface of the substrate 102 and may include two or more stacks of different quantum well structures that have intraband transitions at different wavelengths to allow each column 110 to detect radiation of different colors. One or more columns 110 may be grouped together to form a single sensing pixel of a sensor array.

A second conductive contact layer 116 is directly formed over the quantum-well stack 114 so that the quantum-well stack 114 is sandwiched between the contact layers 112 and 116. Different electrical potentials are applied to the layers 112

and 116 to properly bias the quantum-well stack 114. Heavily-doped semiconductor materials (e.g., GaAs) may be used as the contact layers 112 and 114.

The gap 120 between adjacent columns 110 is formed by removing quantum-well layers and other layers above the substrate 102 by, e.g., etching. The gap 120 may be etched slightly into the substrate 102 to ensure complete separation between any two adjacent columns 110. The gap 120 is electrically insulating and may be filled with vacuum, air, or an insulating material. The index of refraction of the gap 120 is less than that of each quantum-well column 110. Hence, each column 110 is an independent sensor which is electrically isolated from other columns.

Different columns 110, however, are not completely separated in their optical properties. The array of the columns 110 is a periodic structure and hence can be collectively used to construct a two-dimensional optical grating. This grating can be used to couple a portion of the incident radiation into each quantum-well column 110 with a polarization perpendicular to the quantum-well layers. It has been discovered that the coupling efficiency of this grating can be increased by forming a metallic grating tooth 118 on top of each quantum-well column 110. The grating tooth 118 may be a square layer formed of gold, for example.

In addition, this array of columns 110 is optically different from a conventional diffraction grating. Its bandwidth is broader, to allow detection of different wavelengths within its bandwidth. FIG. 2 compares the absorption bandwidths of a grating-coupled quantum-well sensor without slots and a slotted quantum-well sensor.

Each quantum-well column 110 also functions as an optical cavity with its side walls forming its reflective surfaces.

Since the refractive index of the quantum-well column 110 is selected to be greater than that of the gap 120, certain rays entering the column 110 from the substrate 102 may undergo one or more total internal reflections. In this sense, each quantum-well column 110 is also a waveguide. Hence, the actual interaction length is increased. The absorption by the quantum-well layers is correspondingly increased. This further increases the coupling efficiency of the device 100. Certain parameters of each column 110, including column width, gap width, and gap index, are adjusted to achieve a resonance condition of the optical cavity, to increase the magnitude of the electric field perpendicular to the quantum-well layers and therefore the coupling efficiency. Measurements also indicate that these quantum-well columns 110 exhibit weak optical coupling to a certain extent.

Another feature of the slotted quantum-well sensor 100 is its reduced dark current. The dark current is approximately proportional to the dimension of the cross section (i.e., the square root of the area) of the quantum-well region in a quantum-well sensor. The presence of the gap 120 between adjacent quantum-well columns 110 reduces the cross-sectional area of the quantum-well layers and hence the dark current as compared to a sensor without the gap 120.

FIG. 3 shows a structure of a 1-dimensional array of quantum-well columns. FIG. 4 shows the calculated magnitude of the coupled radiation with its electric field (E_z) perpendicular to the quantum-well layers for a grating-coupled quantum-well sensor similarly constructed as in FIG. 2 but without slots. As a comparison, FIGS. 5 and 6 respectively show the calculated electric field (E_z) in the quantum-well layers for sensors with and without the grating teeth. The calculations are performed by solving a finite-difference

Helmholtz equation. The calculation results suggest that the coupling efficiency of the slotted sensor shown in FIG. 5 is triple the coupling efficiency of a non-slotted sensor shown in FIG. 4 even after about 30% of the quantum-well material is removed. In addition, the presence of the grating teeth in the slotted sensor plays a significant role in achieving the excellent coupling efficiency.

Although only a few embodiments are disclosed, other embodiments, variations, and modifications are to be encompassed by the following claims.